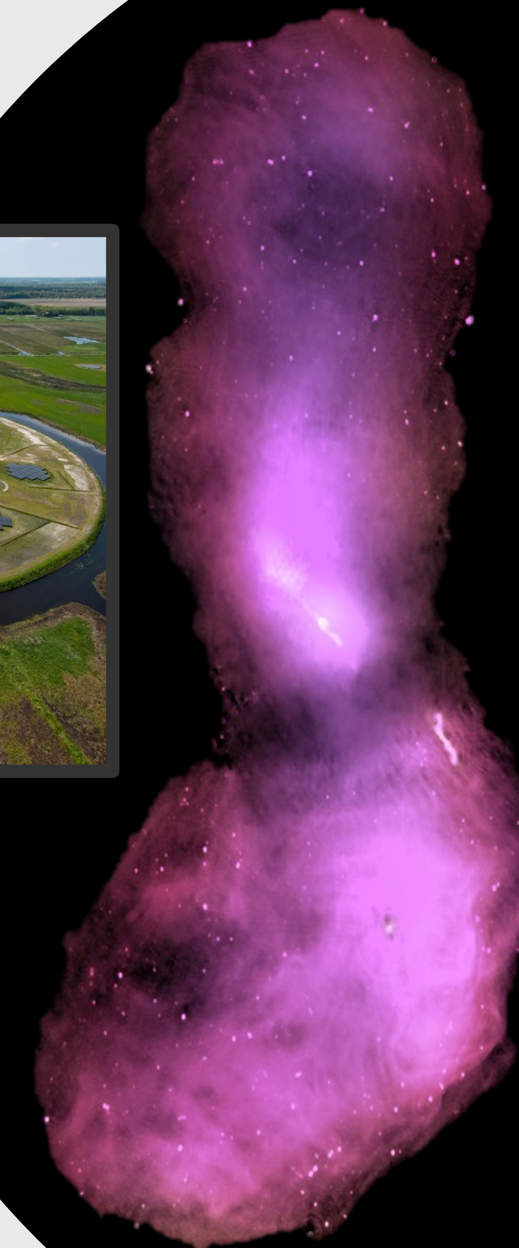
Introduction to (deep, dark world) of calibration



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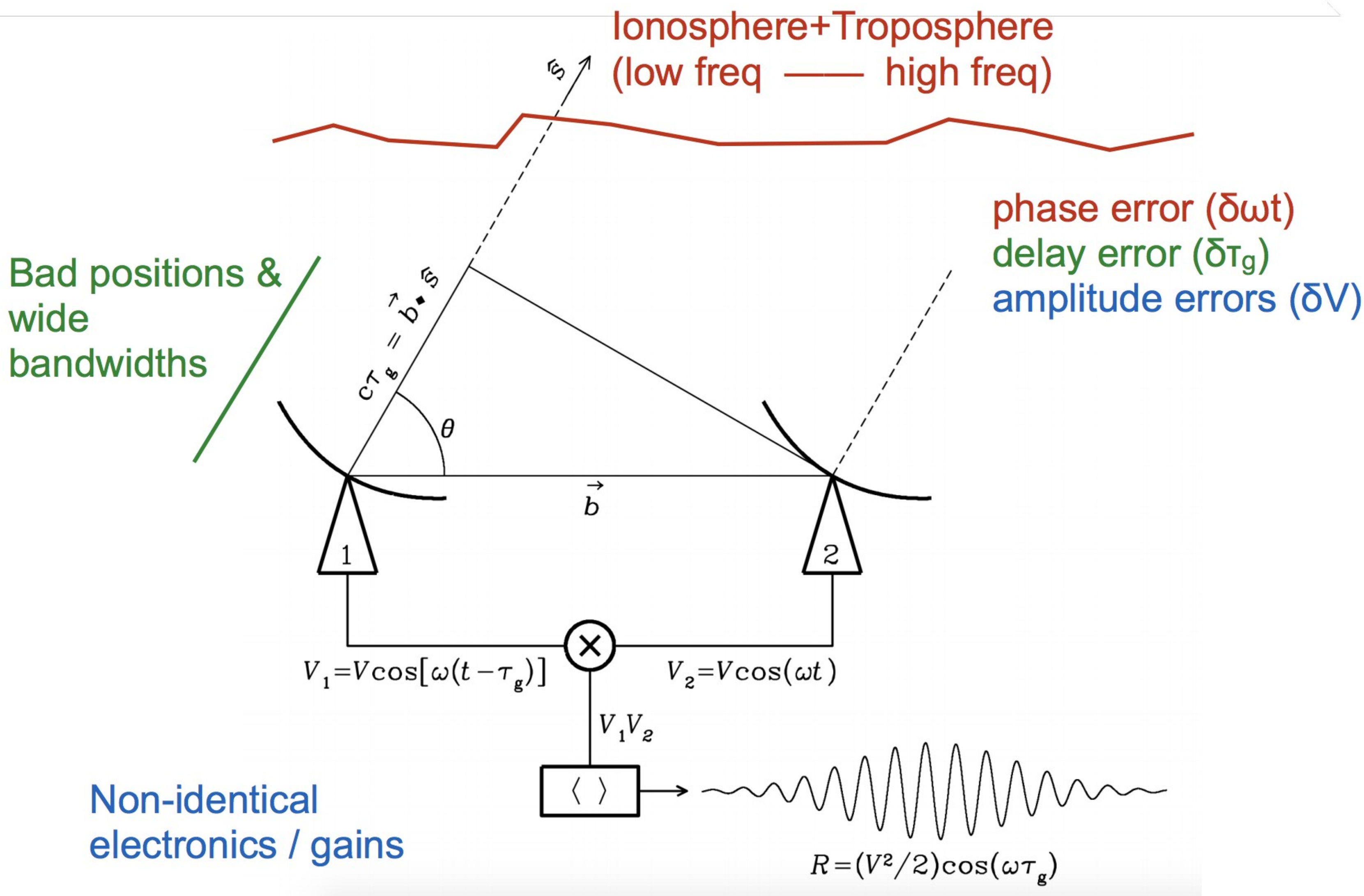
Kenyan Radio Astronomy School,
Nairobi, Kenya
29th of May 2018

VLBI

EVN made of

Calibration is to fix this mess…



Solve for these issues using calibration

Some of the key features

- Relevant physical effects:

Antenna/feed
- System temperature
- Primary beam
- Pointing
- Position (location)

Atmosphere
- Ionosphere
- Troposphere
- water vapor

Digitiser/Correlator
- Auto-leveling
- Baseline errors

LNA+conversion chain
- Clock
- Gain, phase, delay
- Frequency response

Lack of knowledge?

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- We want to parameterize our knowledge of the system.

- We do this by **the radio interferometry measurement equation** (RIME) which relates the observed (perturbed) visibility to the ideal (unperturbed, "true") visibility.

Jones matrix for antenna *i*

$$\vec{V}_{ij} = J_{ij} \vec{V}_{ij}^{\mathrm{IDEAL}} \quad \text{where} \quad J_{ij} = J_i \times J_j^*$$

observed visibility

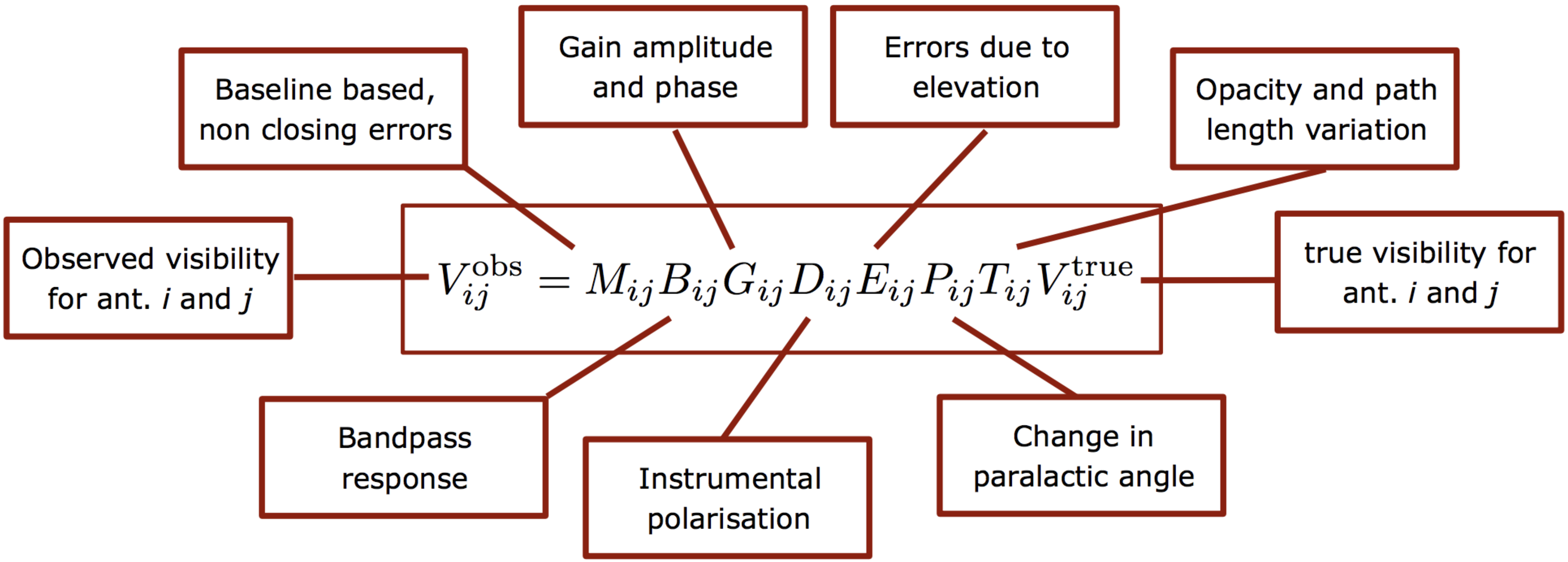
ideal visibility

Combined Jones matrix

- The Jones matrix encodes everything that "happens" to the signal from source to correlator

- Note this assumes calibration parameters should be antenna-based (we will see later that they can be baselines dependent)

CASA's formalisation of RIME



Calibration solves for each Jones matrix (when required) given a **model** for the sky.

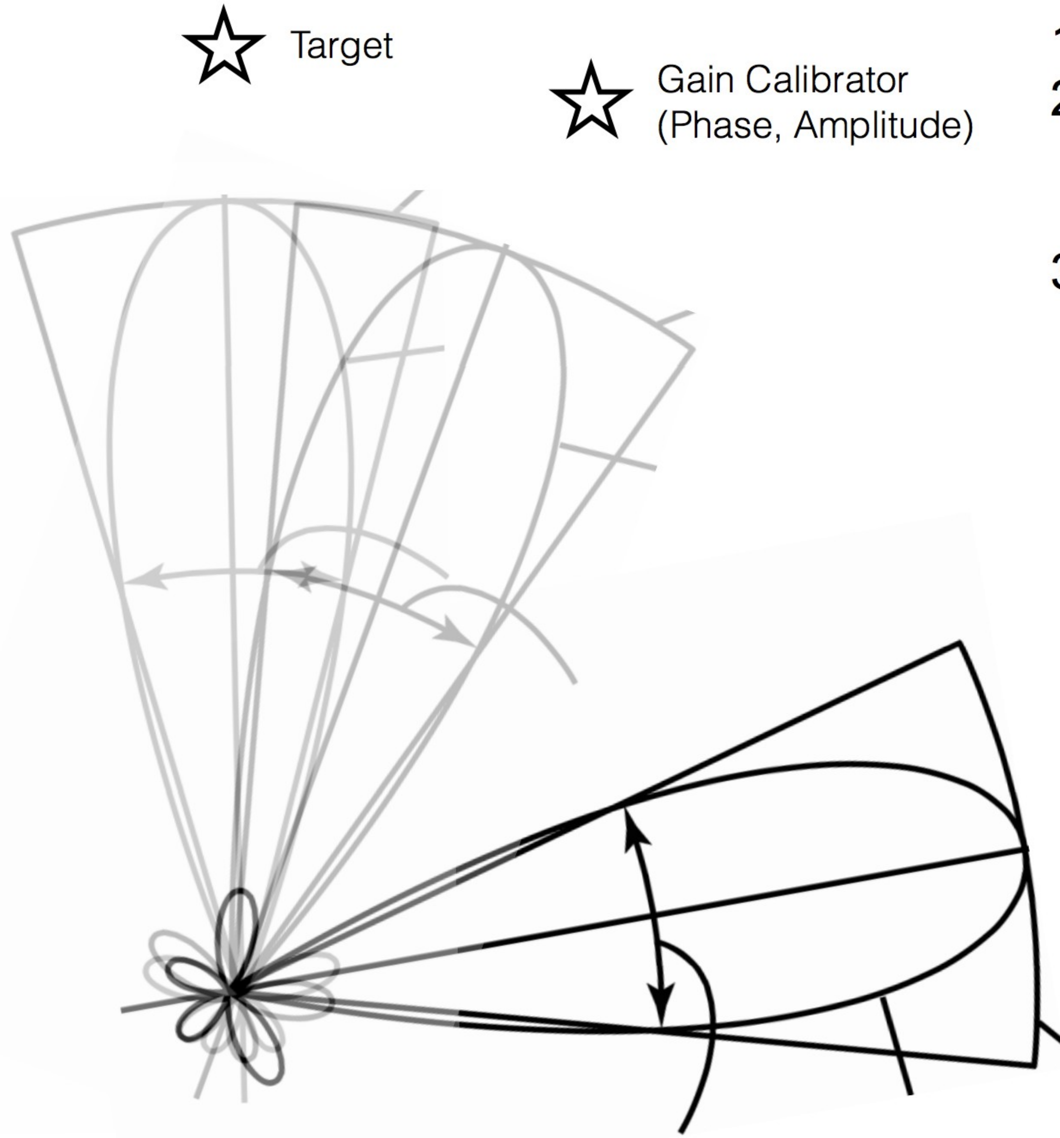
Calibration Strategy

$$V_{ij}^{\mathrm{obs}} = M_{ij} B_{ij} G_{ij} D_{ij} E_{ij} P_{ij} T_{ij} V_{ij}^{\mathrm{true}}$$

- Three levels:
  1. Primary Calibration: use of a “known” standard source to determine timeand direction-independent quantities e.g. B_{pq}
  2. Secondary Calibration: estimate local time-dependent conditions with nearby calibrator
  3. Self-Calibration: use of the target field itself to determine highly time dependent quantities, e.g. the phase of G_{pq}

Calibration Strategy

1. Observe **source**
2. Observe **calibrator** to measure gains (amplitude and phase) as a function of time.
3. Observe **bright calibrator** of known flux-density and spectrum to measure absolute flux calibration, band-pass and residual delays



Choosing Calibrators

- Primary/secondary calibrators should have:
  - Excellent positions (for astrometry)
  - Proper source size ("just compact enough") - standard calibrator lists
  - Compact enough to be unresolved on the longest baselines but not so compact that the source is variable

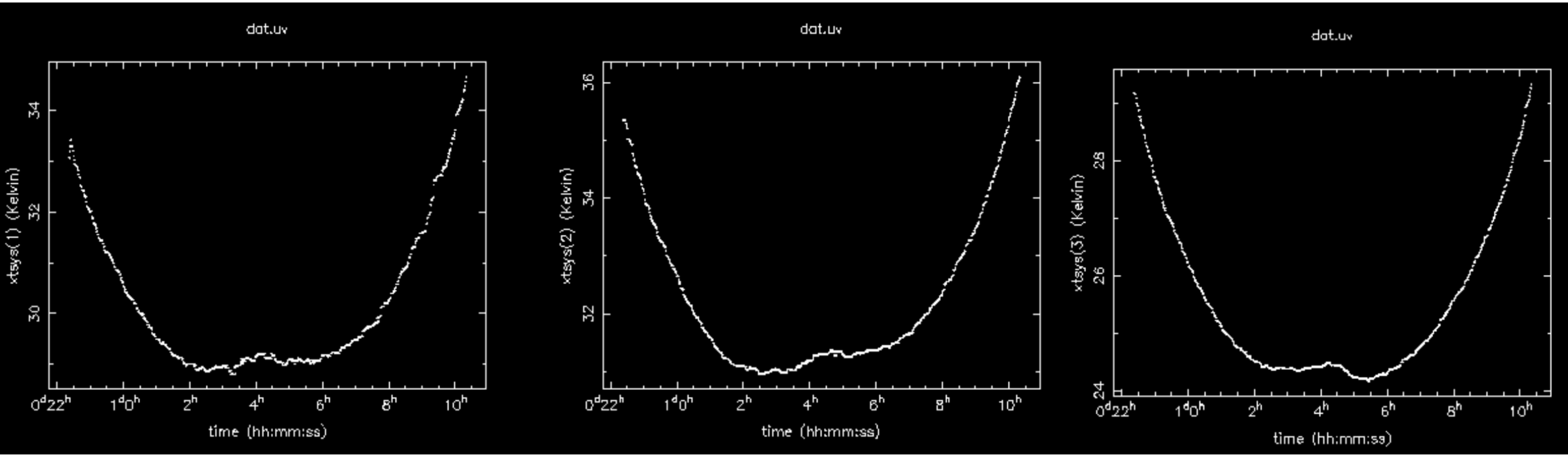
- Well-understood flux density (for flux scale) and spectral shape (for bandpass)

- For polarization calibration: well understood polarimetric properties (including Faraday rotation measure, where appropriate)

System Temperature Calibration

$$V_{ij}^{\mathrm{obs}} = M_{ij} B_{ij} G_{ij} D_{ij} E_{ij} P_{ij} T_{ij} V_{ij}^{\mathrm{true}}$$

- Rule of thumb: don’t solve for things that can be determined in other ways
  - Example: system temperature (Tsys), a time-dependent measure of the sensitivity of each antenna
    - Often measured directly (using on-dish calibrator source) and included with visibility data
    - When available, apply it first!
    - Example: 3 WSRT antennas (measured T_{sys} values for the X feed):

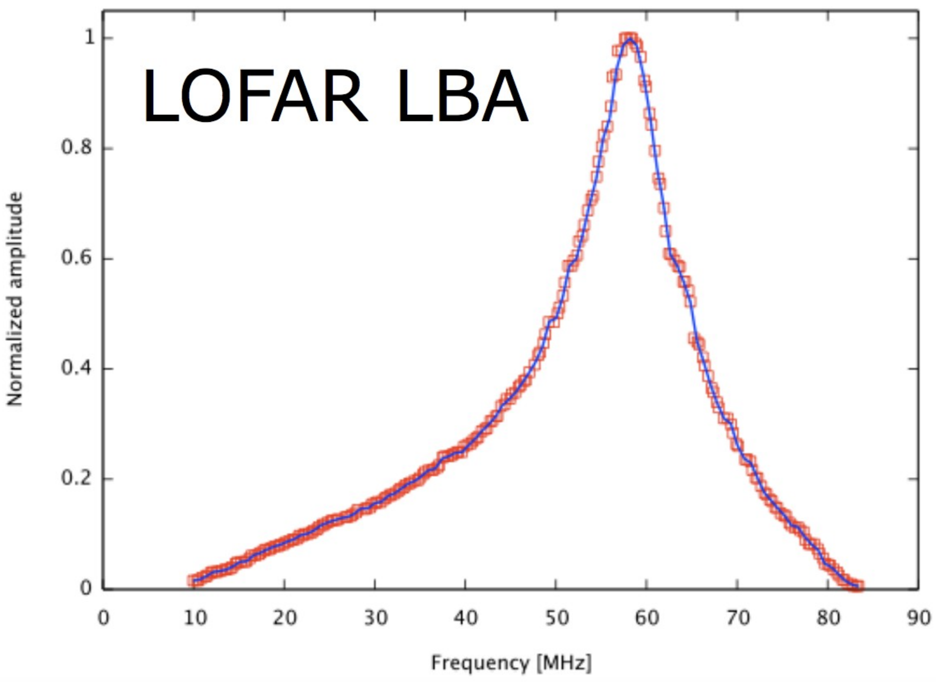


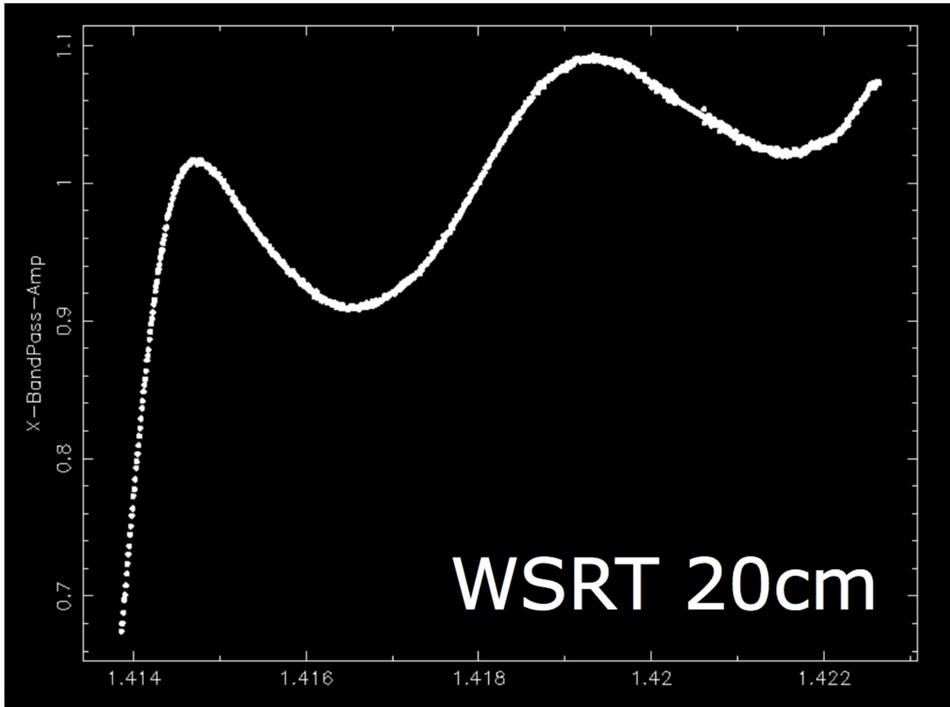
Bandpass calibration

$$V_{ij}^{\rm obs} = M_{ij} B_{ij} G_{ij} D_{ij} E_{ij} P_{ij} T_{ij} V_{ij}^{\rm true}$$

- The bandpass captures the frequency dependent sensitivity across the observed frequency range (which has features due to filters, inherent sensitivity variations, and possibly signal processing artifacts)

$$\mathbf{B} = \begin{pmatrix} B_x(\nu) & 0 \\ 0 & B_y(\nu) \end{pmatrix}$$





Example Delay Calibration

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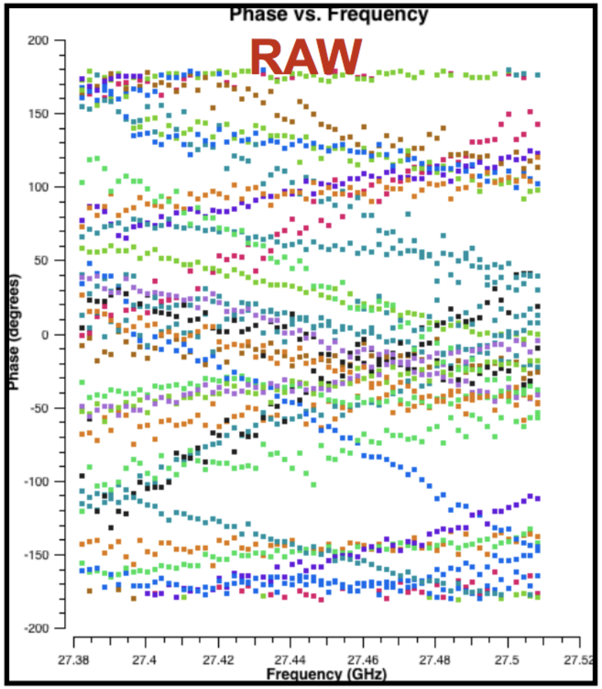
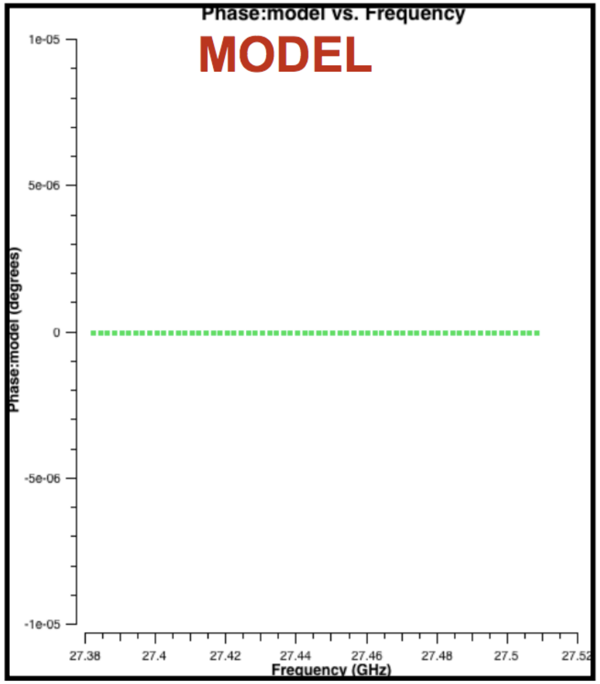
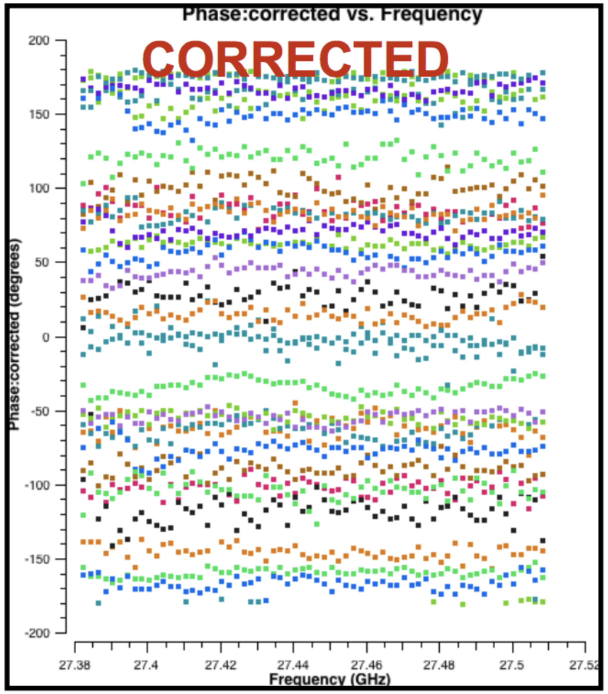
Here is an observed visibility function (delay), the ideal visibility function and the calibrated data (after solving the K_{ij} in the the measurement equation).

Main source of delay error: Large fractional bandwidths.





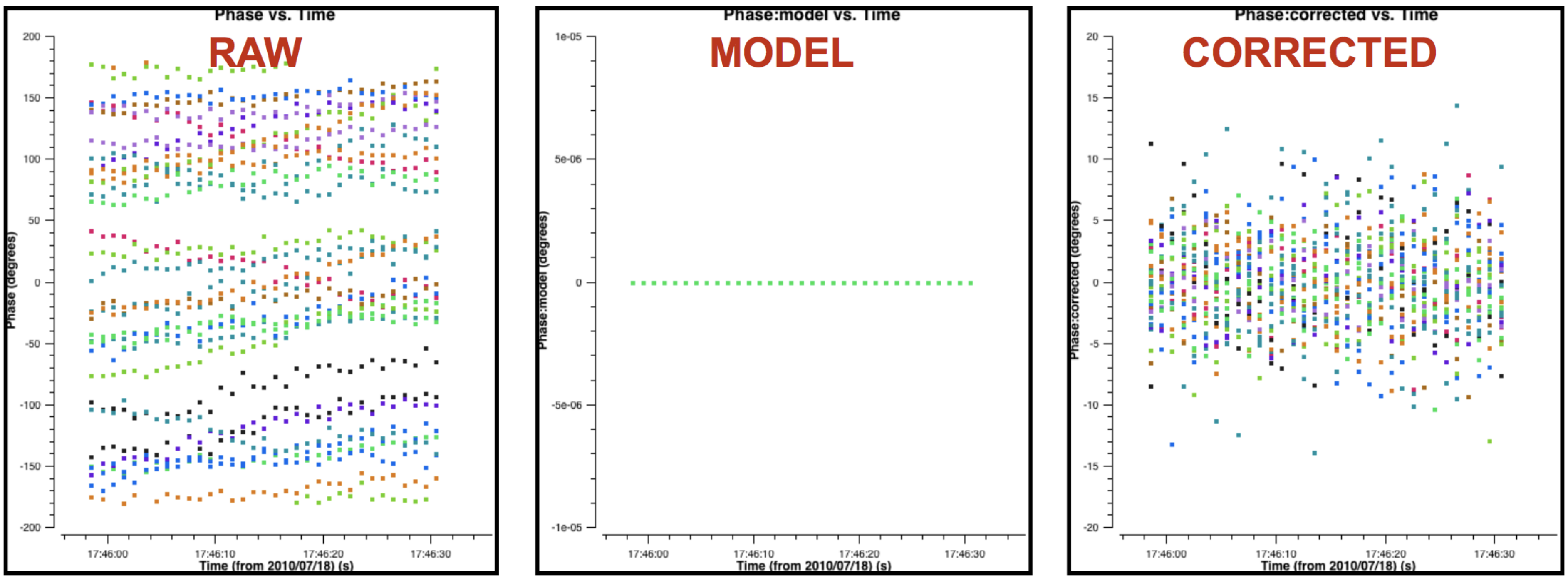


Example phase calibration

$$V_{ij}^{\mathrm{obs}} = M_{ij} B_{ij} G_{ij} D_{ij} E_{ij} P_{ij} T_{ij} V_{ij}^{\mathrm{true}}$$

Here is an observed visibility function (phase), the ideal visibility function and the calibrated data (after solving the G_{ij} in the the measurement equation).

Main source of phase error: Variable ionosphere or troposphere + electronics.

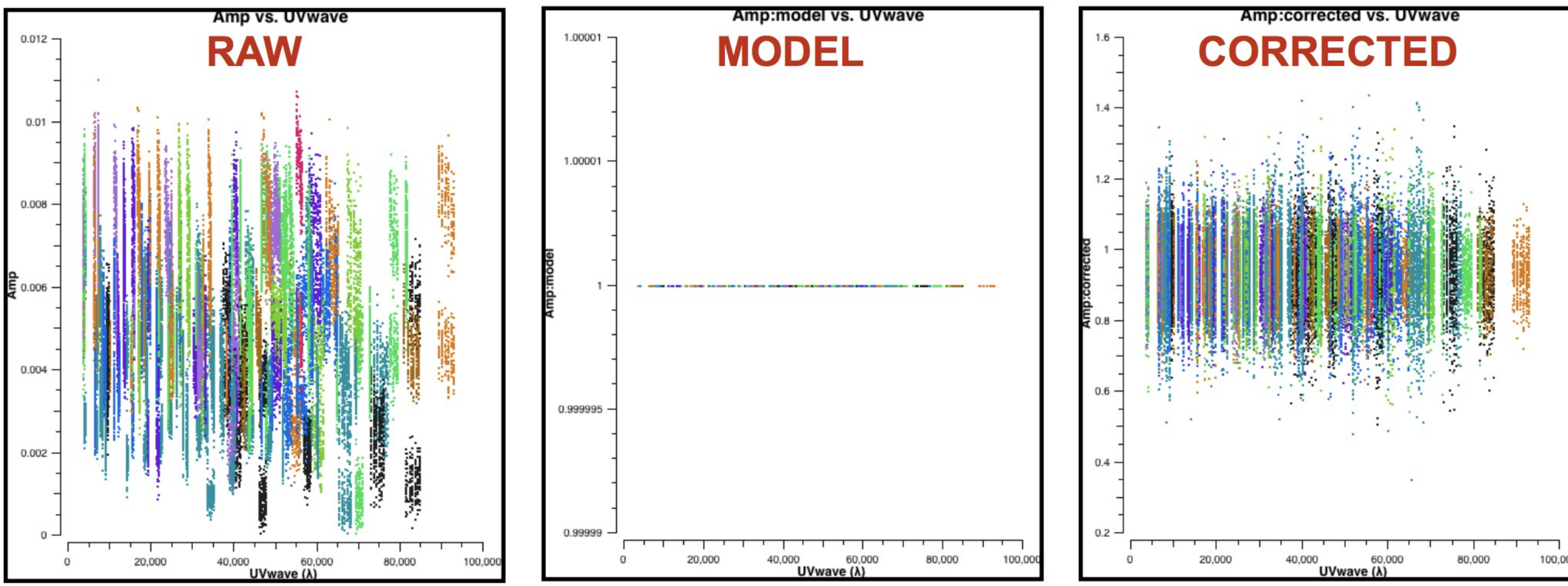


Example Amplitude Calibration

$$V_{ij}^{\text{obs}} = M_{ij} B_{ij} G_{ij} D_{ij} E_{ij} P_{ij} T_{ij} V_{ij}^{\text{true}}$$

Here is an observed visibility function (amplitude), the ideal visibility function and the calibrated data (after solving the G_{ij} in the the measurement equation).

Main source of amplitude error: Variable gain in the amplifiers of the system.



Each colour represents visibilities with a common antenna.

Possible Cal Statergy(*)

- Load data
- Inspect logs, flag bad data, flag for shadowing (look outside!)
- Calibrate primary calibrator (bandpass, gain, leakage)
- Inspect solutions
- transfer bandpass, gain amplitude (flux scale) and leakage to secondary
- Calibrate secondary calibrator (gain)
- inspect solutions
- transfer bandpass, gains, and leakage to target
- Inspect target for bad data, flag if necessary
- Image, deconvolve, and selfcal if necessary

Conclusions and tips

- Don't be afraid to flag bad data! Corrupted data can reduce the image quality significantly.
- Visualize your data!
- We will look at more complicated calibration strategies next lecture, with a look at closure phases, fringe fitting, and self-calibration
- Thanks John McKean and George Heald